

OMAE2017-62278

STRUCTURAL RELIABILITY ASSESSMENT OF AN OIL TANKER ACCIDENTALLY GROUNDED IN THE ADRIATIC SEA

Maro Ćorak

Faculty of Mechanical Engineering and Naval
Architecture, University of Zagreb
Zagreb, Croatia

Joško Parunov

Faculty of Mechanical Engineering and Naval
Architecture, University of Zagreb
Zagreb, Croatia

C. Guedes Soares

Centre for Marine Technology and
Ocean Engineering (CENTEC),
Instituto Superior Técnico,
Universidade de Lisboa, Portugal.

ABSTRACT

The aim of the paper is to present a methodology for the assessment of the structural reliability of an oil tanker damaged in a hypothetical grounding accident in the Adriatic Sea. The grounding accident affects the ultimate hull girder capacity in the damaged region, the still water bending moment (SWBM) distribution along the vessel as well as the vertical wave bending moments (VWBM). The extent of the damage on the ship's hull after a grounding accident depends on several parameters such as ship's speed, rock size, penetration depth, longitudinal and transversal location of stranding along the hull. These parameters are in the present study assumed as random variables, described by probability density functions. Based on defined statistical properties, random realizations of grounding parameters are simulated by Monte Carlo (MC) simulation. For each such random grounding scenario, the damage size is calculated by the surrogate model based on numerical grounding simulations. Residual ultimate strength and SWBM distribution are determined based on the size and location of the damage. VWBM is calculated for average sea state in the area with increased risk of grounding accident in the Adriatic Sea. Structural reliability analysis is employed to determine the safety index with respect to the ultimate hull girder failure for salvage period of 12 hours. As each grounding scenario results in different hull-girder reliability, histogram of safety indices is obtained representing new measures for the performance assessment of the damaged ship.

1. INTRODUCTION

Research aimed at improving shipping safety, with a focus on accidental loads and on the hull girder strength after collision and grounding, is emphasized as one of the priorities in the field of marine structures [1]. The most common ship accidents are ship-to-ship collisions and groundings [2]. In the case of such an occurrence, the ship strength is reduced, still water loads may increase and wave loads could become a cause of structural overloading. A damaged ship may collapse after a collision or grounding accident if she does not have adequate residual longitudinal strength. Such a collapse can occur when the hull's maximum residual load-carrying capacity is insufficient to sustain the corresponding hull-girder loads applied [3].

An analysis of past accidents involving oil tankers, shows that enclosed waters are especially sensitive to oil tanker accidents. Such enclosed area is the Adriatic Sea, the part of the Mediterranean Sea that separates the Apennine and Balkan peninsulas in the south and the Apennine and Dinara mountains in the north. Across the Mediterranean, the Adriatic Sea tanker traffic is very intense. On the other side, the Adriatic is also extremely important for tourism and fishing, on which the economy of both Italy and Croatia heavily depend. An oil tanker accident with a significant oil spill would therefore cause an irreversible ecological disaster with enormous economic losses [4].

The aim of the present study is to propose a methodology for the assessment of structural reliability of an oil tanker that may be damaged in a grounding accident in the Adriatic Sea.

The grounding affects the ultimate hull girder capacity in the damaged region, the still water bending moment (SWBM) distribution along the vessel as well as the vertical wave bending moments (VWBM). Whether the SWBM will increase or decrease with respect to the intact ship depends on the damage size and location and flooded tanks. For tankers in full load condition, damage of ballast tanks in the midship region is typically the worst situation, leading to considerable increase of the SWBM [5]. The most recent studies indicate that the transfer functions of the VWBM at midship slightly increase as a consequence of the flooding [6]. However, a milder wave environment and reduced exposure time compared to the design condition of the intact ship have a much larger influence on the VWBM.

The extent of the grounding damage on the ship's hull after a grounding accident depends on several parameters such as ship's speed, rock size, penetration depth, longitudinal and transversal location of stranding along the hull. These parameters are assumed in the present study as random variables, described by probability density functions. Random realizations of collision parameters are defined by Monte Carlo (MC) simulation. For each such random realization, damage size is calculated by the surrogate model based on numerical grounding simulations [7]. The procedure is briefly described in the Section 2. For the resulting damage size and location, residual ultimate longitudinal strength as well as the SWBM distribution accounting for flooding of damaged compartments are determined in Sections 3 and 4. Environmental conditions and wave loads on the damaged oil tanker in the Adriatic Sea are described in Section 5. In Section 6, structural reliability approach is used to calculate failure probability during the salvage period for each randomly realized grounding event. Resulting safety indices are presented in the form of histogram. The approach represents advancement with respect to the state of the art, because so far structural reliability studies have been mostly done by assuming damage according to different Rules or Guidance Notes of classification societies [8, 9].

2. GROUNDING ACCIDENT IN THE ADRIATIC SEA

2.1. Grounding damage

Different methods, from empirical and statistical models [10] to numerical simulations can be used for the assessment of grounding accidents. Experiments and nonlinear finite element methods (NLFEM) provide the most straightforward understanding of structural failure mechanisms of complex events such as ship grounding. However, such methods are still expensive since are time-consuming in terms of modelling and computation and require detailed description of the ship structural configurations. Simplified models suitable to quickly assess the damage due to grounding accident, where only limited information regarding the ship is available are essential

for structural reliability assessment of large number of random realizations. Therefore, in the present study the rapid prediction of grounding behavior of double bottom tankers is analyzed based on the Hainvee's PhD thesis [7]. The thesis and corresponding references [11-13] comprises the method development and application example of simplified formulas which were obtained by the surrogate model based on 150 numerical grounding simulations. Simplified formulas for the grounding resistance and damage size opening width in the outer and inner plating of a double bottom tanker are developed based on a series of numerical simulations conducted with tankers of different lengths. First, the simplified formula was developed for the average grounding force as a function of penetration depth and the parameters describing the rock size and ship size. To derive universal equation for different rock and ship sizes, the grounding resistance F was evaluated as a function of contact pressure and the contact area as [11]:

$$F(L, a, \delta, h_{db}) = P \cdot A = f_{c_T}(L) \cdot \bar{P}(a) \cdot A(a, \delta, h_{db}) \quad (1)$$

where $f_{c_T}(L)$ is the function that characterizes the structural resistance level of the ship as a function of its length L , $\bar{P}(a)$ is the normalized ship size-independent contact pressure as a function of the rock size a and $A(a, \delta, h_{db})$ is the contact area between the rock and the double bottom structure. The contact area A is a function of the penetration depth δ , the rock size a and double bottom height h_{db} [3]. The shapes of the rocks were given with the parabolic equation where a single parameter a defines the rock size:

$$z = \frac{y^2}{a} \quad (2)$$

where z and y denote the vertical and horizontal coordinate. Lower values of a correspond to sharp rocks, while large values of parameter a describe blunt "shoal"-type rock.

If the rock is positioned directly under the longitudinal bulkhead then Eq. (1) should be updated with additional term which depends on penetration depth δ [13].

The damage opening size is defined with the length and the width of the damage in the outer and inner shells of the ship's double bottom. Damage opening length is measured along the longitudinal direction of the ship and for simplicity it is assumed that the opening lengths in the outer and in the inner bottom are equal. The damage length l_{dam} , is calculated by equalizing the work done by the grounding force F with the kinetic energy of the ship [12]:

$$F \cdot l_{dam} = \frac{\Delta \cdot v^2}{2} \rightarrow l_{dam} = \frac{\Delta(1+a_x) \cdot v^2}{2 \cdot F} \quad (3)$$

where Δ is ship's displacement, a_x in non-dimensional surge added mass and v is ship's speed.

2.2. Grounding scenario of Aframax tanker in the Adriatic Sea

As can be seen from the previous Section, the extent of the damage on the ship's hull after a grounding accident depends on several parameters like ship's speed, rock size, penetration depth, longitudinal and transversal location of grounding along the hull. These parameters are in the present study assumed as random variables, described by probability density functions (PDF). The probability density functions are assumed according geographical location and also according to the IMO MEPC [14]. In the present analysis, an Aframax class tanker sailing in the Adriatic Sea is considered as the grounded ship. The main particulars of the ship are listed in Table 1.

Table 1. Main particulars of stranded ship.

	Grounded ship
L_{pp}	236 m
B	42 m
D	21 m
Scantling draught	15.1 m
Displacement	120000 t
Max. service speed	15.3 kn

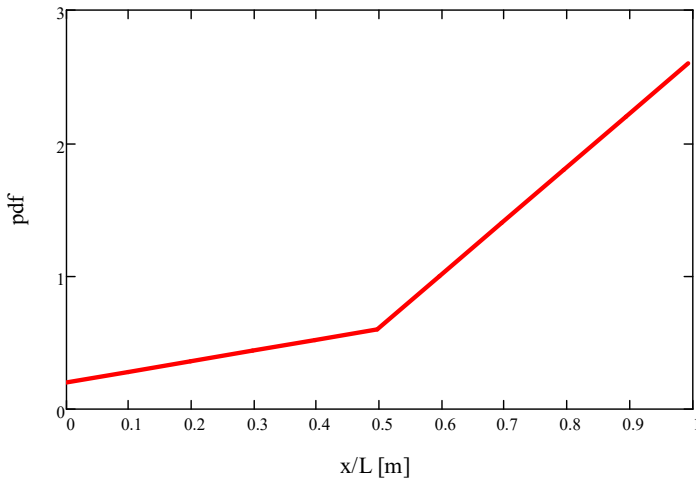


Fig. 1: Probability density function of longitudinal location x of grounding along the hull [14]

The probability distribution of the grounding vessel speed is modelled by a logistic distribution with location

parameter of 12.7 and scale parameter which equals 1.2 [15]. The maximum speed is restricted to the maximum tanker service speed of 15.3 kn. These data are obtained for the Baltic Sea, similar closed sea basin as is the Adriatic Sea [15]. Probability distribution functions of transverse and longitudinal location of grounding along the hull and vertical penetration depth are assumed according to the IMO MEPC [14]. PDF of transverse location of grounding is assumed as uniform distribution from $-B/2$ to $B/2$ (around ship centerline). The probability of the longitudinal location can be seen in Figure 1, which shows that it is most likely that the stranding starts in the forward part of the ship.

From Figure 2., it can be concluded that the penetration depth δ will not be higher than 30% of ship's height D and that majority of random realizations of penetration depth will be smaller than 10% of ship's height.

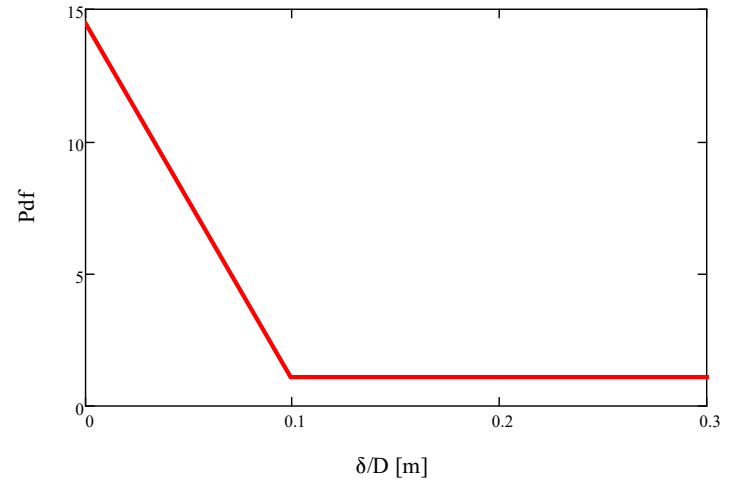


Fig. 2: Probability density function of vertical penetration δ [14]

In the Adriatic Sea, narrow and sharp rocks have higher probability of occurrence compared to the larger wide rocks. Therefore, the probability density function of the rock size a is assumed in the triangular shape with maximum value for $a=3$, and then gradually decreasing to zero for $a=12$. Formulas used in grounding simulation are developed in the thesis for that range of rock sizes [7].

From previously described statistical properties, random realizations of five grounding parameters are simulated by Monte Carlo (MC) simulation. A total of 1000 simulations is performed, which is considered as a sufficiently large sample, because average grounding scenarios are of more interest and relevance than extremely rare and consequently unlikely stranding scenarios that may occur with probability less than 1/1000.

For each realization of grounding parameters, damage sizes of Aframax tanker are calculated using simplified formulas from method described in Section 2.1. Simulated rock size is

shown in Figure 3. The damage length l_{dam} , is calculated using Eq. (2) and results are presented in the Figure 4. It is evident that in some cases, especially in the case of high speed the damage length becomes equal to the ship length indicating that the kinetic energy of the ship exceeds the energy absorbed by structural deformations. When the energy of structural deformations increases, i.e. when inner bottom is breached, the number of cases with long damages decreases.

Opening widths in the outer shell and inner bottom are also calculated using simplified formulas from described method. The results are presented in Figure 5, with respect to the vertical penetration depth. These damages are used to calculate the reduction of the residual strength of the ship hull.

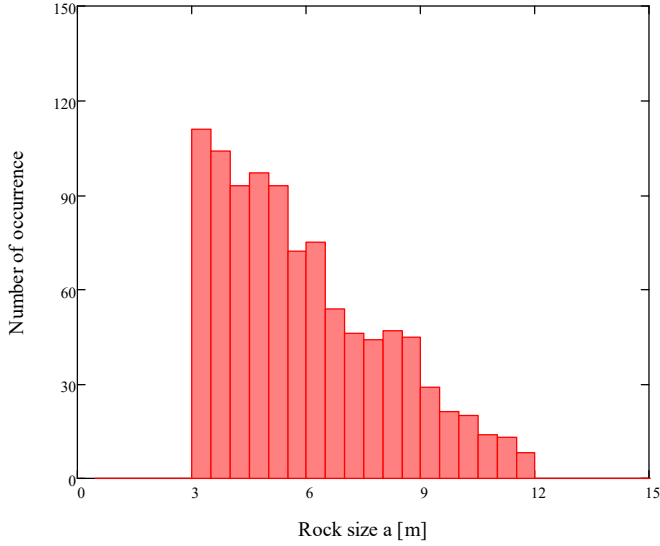


Fig. 3: Random realizations from Monte Carlo simulation of the rock size a based on the assumed PDF

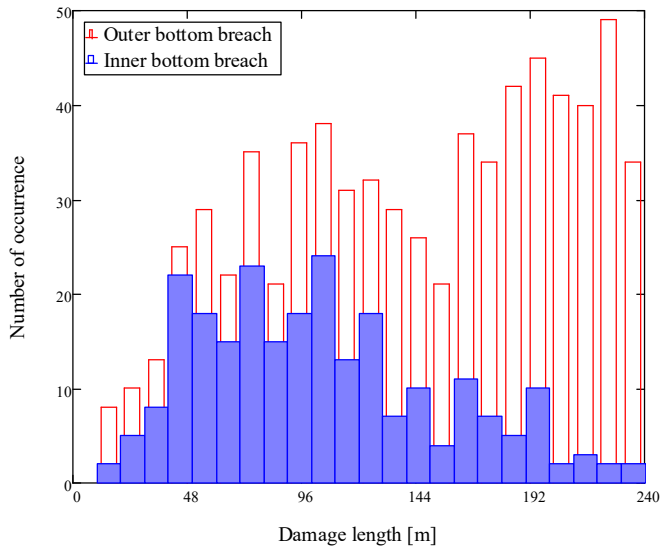


Fig. 4: Damage length

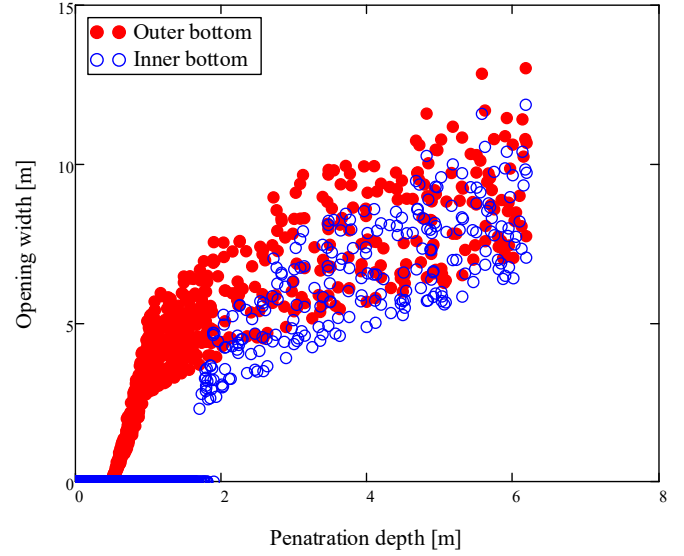


Fig. 5: Opening widths in the outer shell and inner bottom

3. HULL-GIRDER RESIDUAL ULTIMATE LONGITUDINAL STRENGTH

A damaged ship may collapse after the grounding if she does not have an adequate longitudinal strength. Such collapse can occur when the hull's maximum load-carrying capacity is insufficient to sustain the corresponding hull girder loads applied. The approach generally adopted in the calculation of the residual ultimate longitudinal strength of damaged ship considers that the elements within the damaged area are removed and the ultimate strength of the ship is recalculated using the simplified methods [16]. In the present study the assessment of the sagging ultimate longitudinal strength of Aframax oil tanker (Table 1), damaged in a hypothetical grounding accident is calculated using an innovative Paik et al. method [17], assuming that grounding is caused by conically shaped rock. Reduction of the ultimate strength is calculated by regression equations developed by Kim et al. [18] using concept of grounding damage index (GDI). The GDI takes into account the extent and the location of grounding damage for both, inner and outer bottom structures. The grounding damages, calculated by simplified formulas in the previous Section, together with the correction factor (α), reflecting the contribution of the inner bottom structure to the ultimate longitudinal strength of the ship, enable calculation of GDI [17]:

$$GDI = \frac{A_{ro}}{A_{oo}} + \alpha \cdot \frac{A_{ri}}{A_{oi}} \quad (4)$$

where A_{ois} , A_{oo} are original (intact) areas of the inner and outer bottom respectively; A_{ris} , A_{ro} are reduced (damaged) areas of the inner and outer bottom. Correction factor α of Aframax oil tanker in sagging condition is calculated by the ALPS/HULL

Intelligent Supersize Finite Element Method (ISFEM) and depends on the double bottom height h_{db} and ships height D as [17]:

$$\alpha = -6.843 \cdot \frac{h_{db}}{D} + 0.9845 \quad (5)$$

Finally, using the described method, the relationship between the reduction of the ultimate strength in sagging and the GDI can be formulated as [17]:

$$\frac{M_U}{M_{U0}} = -0.2069 \cdot GDI^2 - 0.1387 \cdot GDI + 1 \quad (6)$$

where M_U and M_{U0} are the ultimate longitudinal strength in sagging of the damaged and intact ship, respectively.

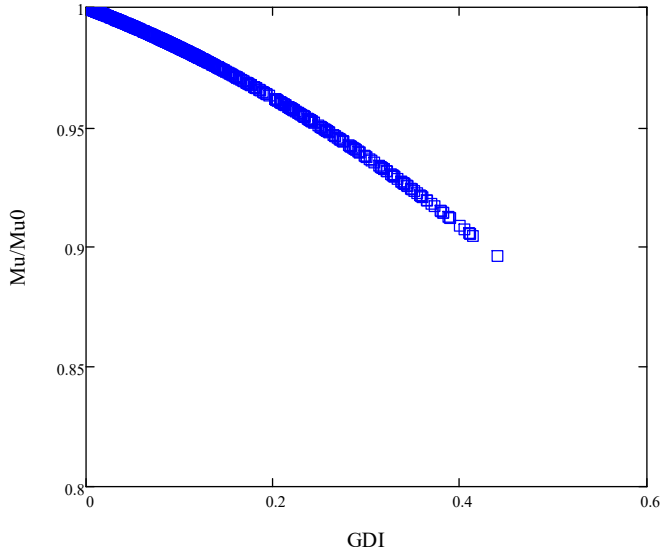


Fig. 6: Relationship between reduction of the residual strength in sagging and the GDI for simulated cases

Results of the residual strength calculations in sagging of the considered Aframax tanker for all assumed grounding accidents are shown in Figure 6 and 7. Figure 6 shows decrease of M_u in sagging with increase of GDI . Furthermore, Figure 7 shows the histogram of the percentage of the ultimate bending moment reduction in sagging. It can be seen that reduction of the ultimate bending moment in sagging in many cases will be below 5%, while maximum reduction of the residual strength in few cases is slightly above 10%, with max value of 10.5%. The mean value of ultimate sagging bending moment reduction across all simulations is 1.65, while standard deviation reads 2.09.

The ultimate bending moment capacity of the intact section in sagging is determined by progressive collapse analysis using the MARS software [19, 20]. A calculated value

of the ultimate longitudinal strength of midship section in sagging reads 8470 MNm.

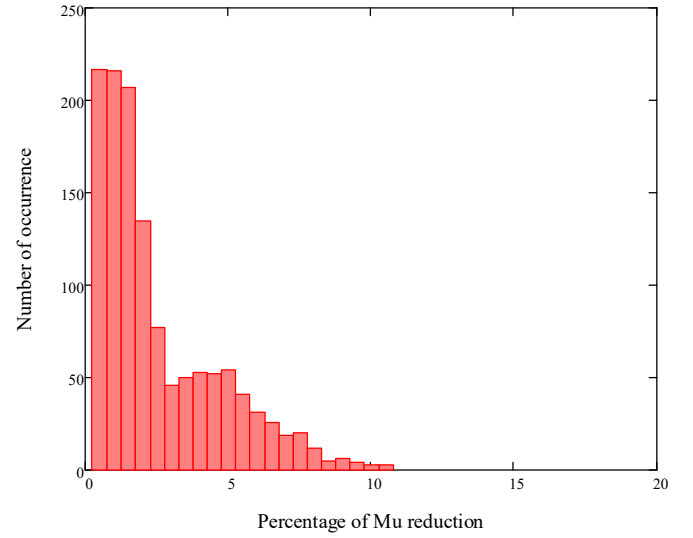


Fig. 7: Histogram of percentage of ultimate sagging bending capacity reduction

For the structural reliability assessment, all uncertainties in the prediction of the ultimate strength are concentrated in a model uncertainty random variable χ_u , which takes into account both the uncertainty in the yield strength and the model uncertainty of the method to assess the ultimate capacity of the midship section, as both variables contribute to the ultimate bending moment. The uncertainty χ_u is defined as a log-normal distribution with a mean value of 1.1 and coefficient of variation of 0.12 [21].

4. SWBM OF A DAMAGED SHIP

Hydrostatic analysis of the damaged ship is performed using commercial software VeriSTAR Stability [22]. For each damage case generated by MC simulation damage length and location of grounding are known. Consequently static equilibrium position and also distribution of the SWBM along the ship are found for detected damaged tanks. Only full-load condition on the scantling draught is considered in the present analysis. The SWBM of the intact ship at midship for that load condition reads 1556 MNm (sagging).

Typical distribution of the SWBM following a grounding damage of midship water ballast tanks (WBT 3-4 P&S) is presented in Figure 8. It can be seen that the maximum SWBM may increase considerably compared to the SWBM in the intact condition. Also, the permissible SWBM for seagoing condition may be largely exceeded in the damaged condition. The results of maximum SWBM for all simulated damage cases are summarized in the form of histogram which is presented in Figure 9. It is evident that in the majority of cases the SWBM in damaged condition is similar as for the intact ship. This also includes damage cases when breach of the bottom shell does not

occur, i.e. the SWBM is not modified at all. However, there is also a certain number of cases where SWBM in damaged condition exceeds the SWBM for the intact ship. The mean value of SWBM across all simulations reads 1386 MNm with standard deviation of 577 MNm, while maximum value of SWBM is 2806 MNm, representing an increase of intact SWBM by factor of 1.8.

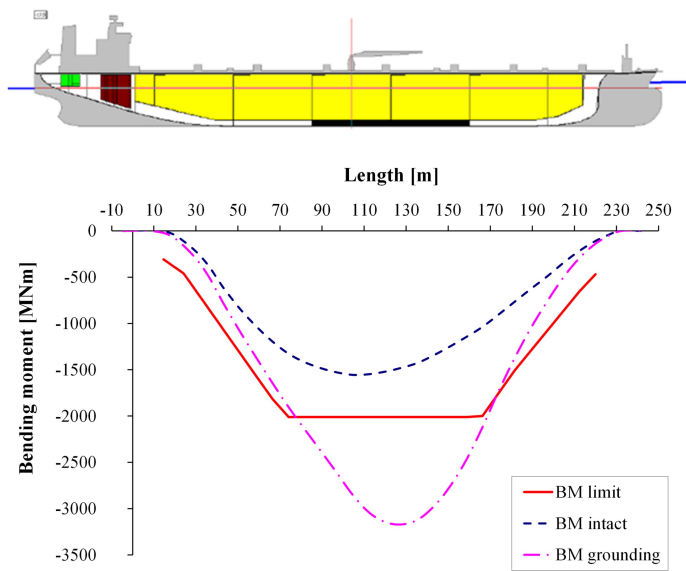


Fig. 8: Comparison of SWBM diagrams for intact and grounding damage of WBT 3-4 (P&S).

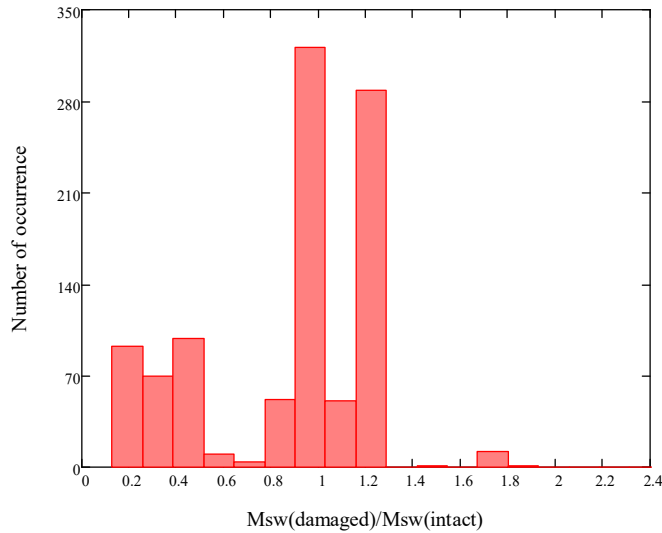


Fig. 9: Histogram of ratio of maximum SWBM in damaged and intact condition for simulated grounding damage cases

In the present structural reliability analysis, the SWBM at midship of the intact ship is taken as a deterministic value since the analysis is done for the particular loading condition. Uncertainties in the calculation of the SWBM are taken into

account by a random variable with mean value equal to 1 and small coefficient of variation of 0.05 [23]. In damaged condition, the SWBM along the vessel is determined by damaged ship stability calculation, as described above. The SWBM in the damaged condition is also taken as deterministic value, whereas model uncertainty is assumed the same as for the intact ship.

5. WAVE LOADS OF A GROUNDED SHIP IN THE ADRIATIC SEA

The grounding accident is assumed to occur at the main sailing route in the Adriatic Sea, where the Croatian island of Palagruža takes the central place. According the study of Zec et al. [24] this location represents the area with increased risk of grounding as presented in Figure 10.

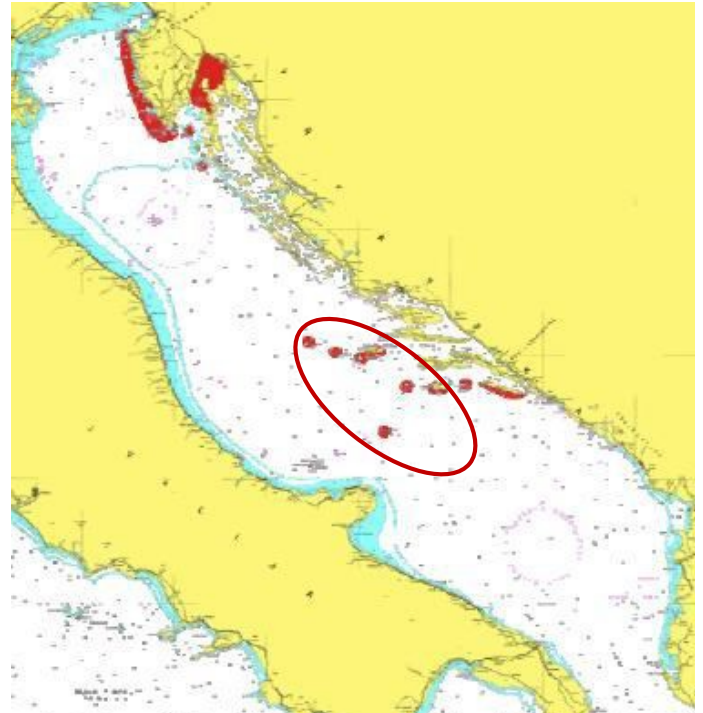


Fig. 10: Adriatic Sea and areas with high risk of grounding [24]

The wave-induced bending moment should be determined based on the wave condition (e.g. significant wave height and wave length, etc.) at the moment of the accident at sea together with the vessel speed in association with a short-term response such as several hours or a couple of days or a couple of weeks during the rescue operation. In the present study, an average sea condition along the ship route in the Adriatic is assumed for the structural reliability assessment of damaged ship. Such average sea condition is calculated for the Palagruža region, using a wave scatter diagram obtain based on calibrated satellite data and numerical wave model simulations from WorldWaves (WWA) database [26] as described by Parunov et al. [27]. Wave loads in short-term sea conditions are

calculated by design charts developed by Parunov and Čorak [25], based on linear 3D panel hydrodynamic method. Only head seas are assumed in the present study, as well as small forward speed of 5 knots. The exposure period until the ship is towed to the safe harbor is assumed to be 12 h, which is reasonable considering the distance from the collision location to the nearest shore in the Adriatic. Based on these assumptions, parameters of the extreme value (Gumbel) distribution of VWBM at amidships are calculated as:

- the most probable extreme value, $x_e^* = 1048$ MNm;
- parameter of the Gumbel distribution, $\alpha_g = 144$ MNm;
- the mean value of Gumbel distribution, $x_c = 1131$ MNm;
- st. deviation of the Gumbel distribution, $\sigma_g = 184$ MNm.

The VWBM is the load effect that exhibits considerable nonlinearity. The effect of nonlinear response is particularly significant for ships with a low block coefficient, leading to large differences between sagging and hogging bending moments. For tanker hull, however, correction for sagging is low and reads 1.03 [21].

Simplifications, assumptions and inaccuracies of the linear engineering models used to predict extreme VWBM on ship hull are taken into account by modelling uncertainty χ_w . For the present reliability study, χ_w is assumed to be a normally distributed random variable with the mean value equal to 1 and coefficient of variation equal to 0.1. The uncertainty of nonlinear effects χ_{nl} is assumed to be a normally distributed variable with mean value equal to nonlinear correction factor 1.03, whereas the coefficient of variation of this uncertainty is assumed to be 0.15 [21].

6. STRUCTURAL RELIABILITY ANALYSIS OF DAMAGED SHIP

Structural reliability analysis of the damaged ship is performed using first-order reliability method for each random damage scenario generated by MC simulation.

With respect to the hull girder ultimate failure under vertical bending moments, following limit state function is used in order to calculate the safety index of the most loaded section:

$$\chi_u M_u - (\chi_{sw} M_{sw} + \chi_w \chi_{nl} M_w) < 0 \quad (7)$$

where M_u is the deterministic ultimate hull-girder bending moment at damaged section; M_{sw} is the deterministic still-water bending moment of damaged ship; M_w is the random variable extreme VWBM; χ_u , χ_w , χ_{nl} and χ_{sw} are the random variables representing the modelling uncertainty of ultimate strength, linear wave load, nonlinearity of wave load and still-water load, respectively. The IMO [28] prescribes that the modelling uncertainties of random variables, which actually represent the lack of knowledge should be modelled by normal distribution with adequate mean value and standard deviation. However, the

IMO suggest that the uncertainty of the ultimate strength should be modelled by log-normal distribution since strength variables cannot take negative value. Taking into account the uncertainty of material yield strength and model uncertainty of the calculation method, the modelling uncertainty of the ultimate strength is thus modelled by log-normal distribution with mean value 1.1 and standard deviation 0.132. Furthermore, the extreme Gumbel distribution of the random VWBM follows from the theoretical results. The summary of the stochastic model employed is presented in Table 2.

Equation (7) represents limit state function for midship section where SWBM is calculated according to damage stability calculations for damage scenario obtained as an outcome of MC simulation while the ultimate bending moment is reduced according to *GDI* for each simulated damage case. It should be mentioned, however, that in about 1/3 of simulated grounding cases, watertight integrity of the ship is not compromised, meaning that there were not changes in SWBM or M_u with respect to the intact ship.

Table 2. Summary of stochastic model adopted.

Variable	Distribution	Mean	COV
M_u (MNm)	Deterministic	Calculated by Equation (6)	
M_{sw} (MNm)	Deterministic	Calculated by damage stability analysis	
M_w (MNm)	Gumbel	1131	0.14
χ_{sw}	Gaussian	1.0	0.05
χ_u	Log-normal	1.1	0.12
χ_w	Gaussian	1.0	0.1
χ_{nl}	Gaussian	1.03	0.15

Thus, for each damage scenario obtained by MC simulation, safety index β is calculated. Safety indices for 1000 MC simulations, are shown in an histogram that is presented in Figure 11. Safety indices β in Figure 11 are grouped in intervals with width of 0.2. It can be seen that the majority of safety indices are within the range $\beta=5.4-5.6$, corresponding to the rather low-failure probabilities $P_f = 3.33e-8$ to $1.07e-8$. The overall minimum $\beta=4.53$ is obtained for the following governing parameters:

- $M_U = 7863$ MNm (7.2% reduction of intact M_U);
- $M_{sw} = 2682$ MNm (172% of intact M_{sw}) (damaged cargo tank from (CT) 1(P&S)/water ballast tank (WBT) 1(P&S) up to CT 4(P&S)/WBT 4(P&S));
- Starting location of grounding, $x=222.8$ m (forward part of the ship).
- Damage length, $l_{dam} = 97.2$ m
- Outer bottom damage breath $B_{out} = 9.7$ m
- Inner bottom damage breath $B_{in} = 8.7$ m
- Ships speed $v=13.1$ kn

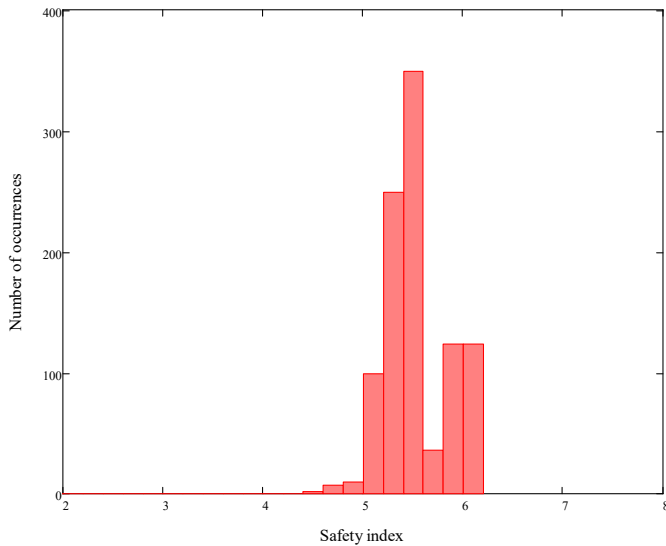


Fig. 11: Histograms of safety indices β obtained by MC simulation

For the intact ship, when $M_U=8470$ MNm and $M_{SWI}=1556$ MNm, $\beta=5.5$. Therefore, it belongs to the interval of 5.4–5.6 in Figure 11, in which 35% of the MC simulations are placed. It is interesting to notice that even 60% of simulated damage cases result in safety index higher or equal to that of the intact ship. This occurs since many damage conditions result in smaller SWBM compared to the intact condition (Figure 9), and consequently in higher safety index. It should be clarified that intact ship means that the ship's structure is not damaged and that the SWBM is therefore not modified because of the damage, whereas the VWBM is taken from Table 2. The mean value of safety index across all simulations is calculated as 5.53, while standard deviation reads 0.32.

7. CONCLUSIONS

Structural reliability of an Aframax oil tanker hypothetically grounded in the Adriatic Sea is performed in the study. The approach is based on Monte Carlo simulation, where random parameters are ship's speed, rock size, penetration depth, longitudinal and transversal location of grounding along the hull.

Damage size is determined by surrogate model from Heinvee [7] based on large number of LS-Dyna numerical simulations. Change in SWBM is obtained by damage stability analysis while residual strength is calculated using Paik's method based on grounding damage index [17].

As a result of the analysis, the safety index is represented in the form of a histogram. It was found that in about 40% of simulated damage cases, the safety index of the damaged ship would be lower compared to the intact ship. The lowest safety index, obtained once in 1000 simulated damage cases, occurs

for the case when 4 pairs of water ballast and cargo tanks are damaged and when ultimate bending capacity is reduced by 7.2% because of the damage.

The histogram of safety indices represents a new measure for the performance assessment of the damaged ship, providing more information compared to the single safety index obtained using assumed deterministic damage. If extended to more severe design wave environments and grounding scenarios, the presented methodology may eventually be suggested for general reliability-based comparison of different alternative designs of ship structures with respect to the grounding damages or for improvement of ship structural design rules.

ACKNOWLEDGMENTS

The work has been fully supported by the Croatian Science Foundation within the project 8658. The WorldWaves data used in the study are provided by Fugro OCEANOR AS.

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